

Towards Attosecond X-Ray Pulses from the FEL

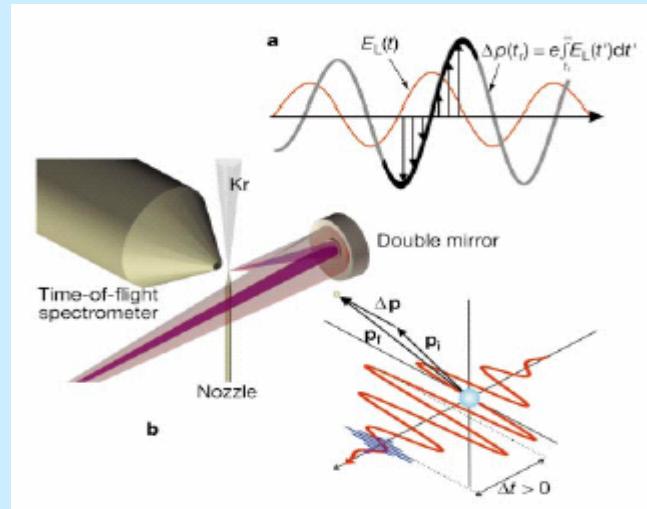
Alexander Zholents and William Fawley

Center for Beam Physics, Lawrence Berkeley National Laboratory



Demonstrated

All optical technique



Nature, vol.414, p.509, 2001

“Attosecond Metrology”

M.Hentachel, *et al.*

Nature, February 26, 2004

“Attomic Transient Recorder”

R.Kienberger, *et al.*

650 attosecond FWHM

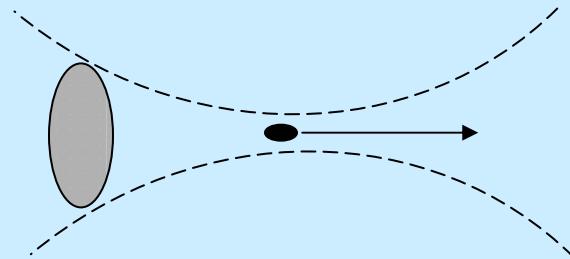
$h\omega=97$ eV

250 attosecond FWHM

$h\omega=97$ eV

Proposals

Laser ponderomotive
interaction with electrons



Optics Communication, vol. 148, p.75, 1998

“Generation of single-cycle attosecond pulses
in the vacuum ultraviolet”
I.Christov, M.Murnane, H.Kapteyn

$h\omega=15 \text{ eV}$

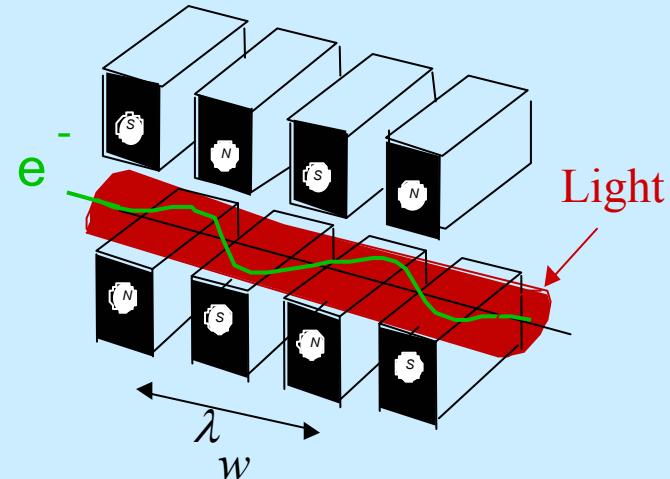
NIM A, vol. 483, p.445, 2002

“Laser driven attosecond SASE x-ray FEL”
M.Zolotorev

$h\omega=10 \text{ keV}$

Proposals

FEL based



Optics Communication, vol. 212, p.377, 2002

“Scheme for attophysics experiments at a x-ray SASE FEL”

E.Saldin, E.Schneidmiller, M.Yurkov

$h\omega=10 \text{ keV}$

no synchronization
to pump pulse

PRL, vol.92, no.7, Feb. 2004, 74801

“Femtosecond and subfemtosecond X-ray pulses from a self-amplified spontaneous-emission-based free-electron laser ”

P.Emma, *et. al.*

$h\omega=8 \text{ keV}$

no synchronization
to pump pulse

FEL based

cont'd

To be published in PRL – subject of this talk

“Intense attosecond radiation from x-ray
FEL ”

A.Zholents, W. Fawley

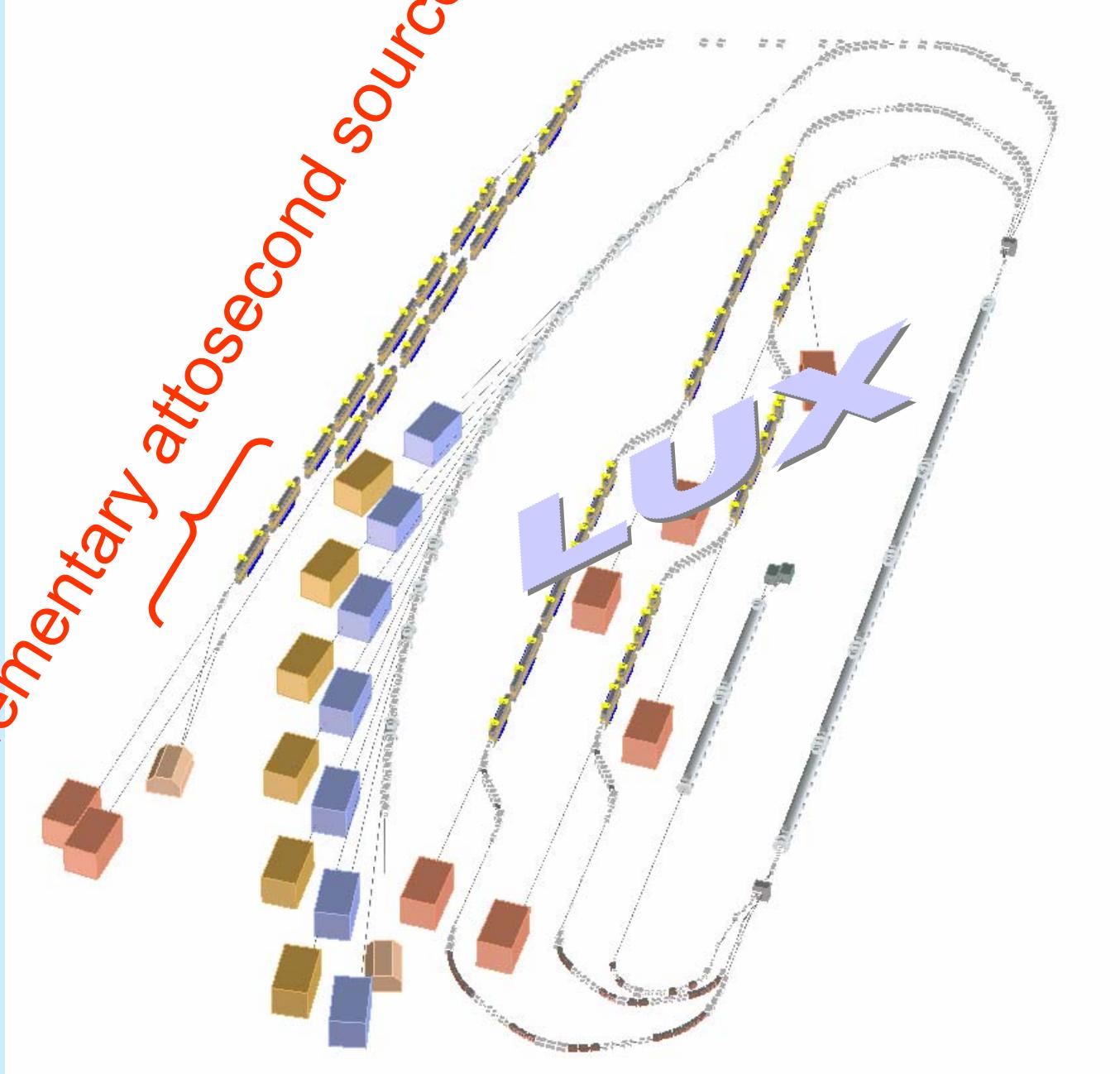
$\hbar\omega=1$ keV

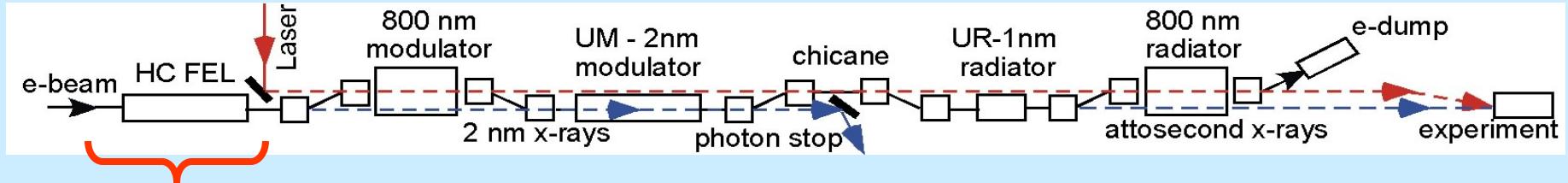
with synchronization
to pump pulse

utilize laser and electron beams

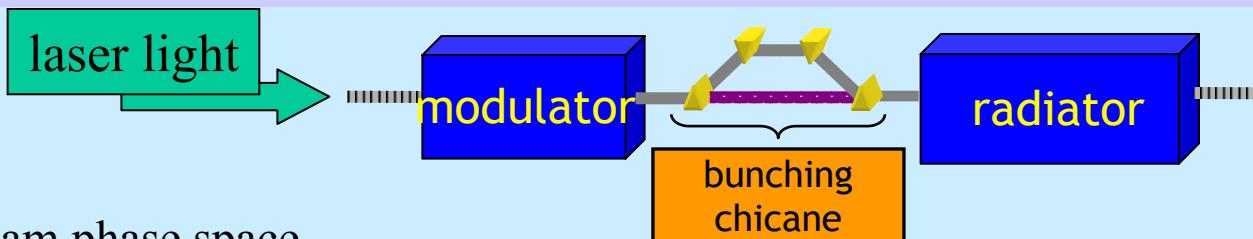


Complementary attosecond source

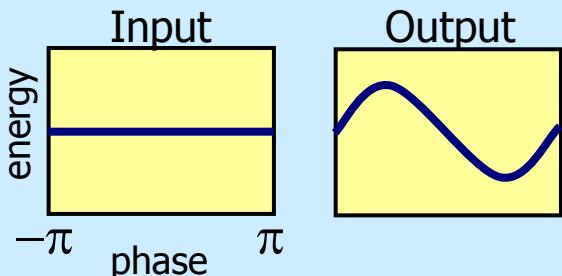




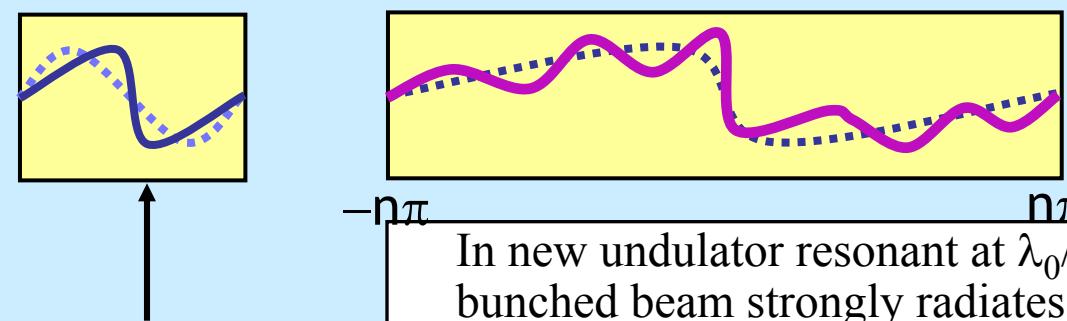
Harmonic Cascade FEL producing 200 MW at 2 nm



e-beam phase space



Energy-modulate e-beam in undulator via FEL resonance with coherent input radiation



Dispersive section,
strongly increase
bunching at
fundamental
wavelength and (non-
linearly) at higher
harmonics

In new undulator resonant at λ_0/n ,
bunched beam strongly radiates
harmonic radiation

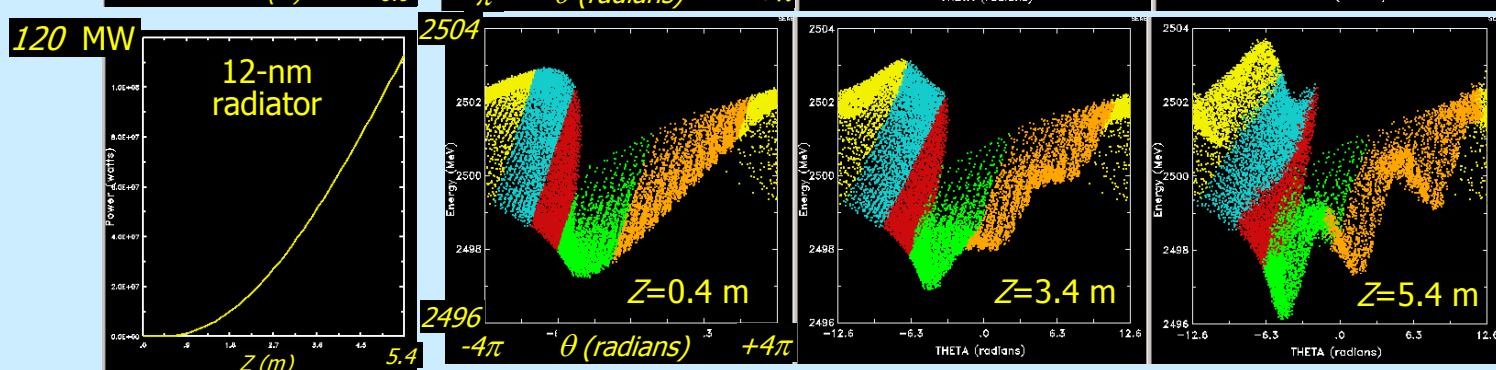
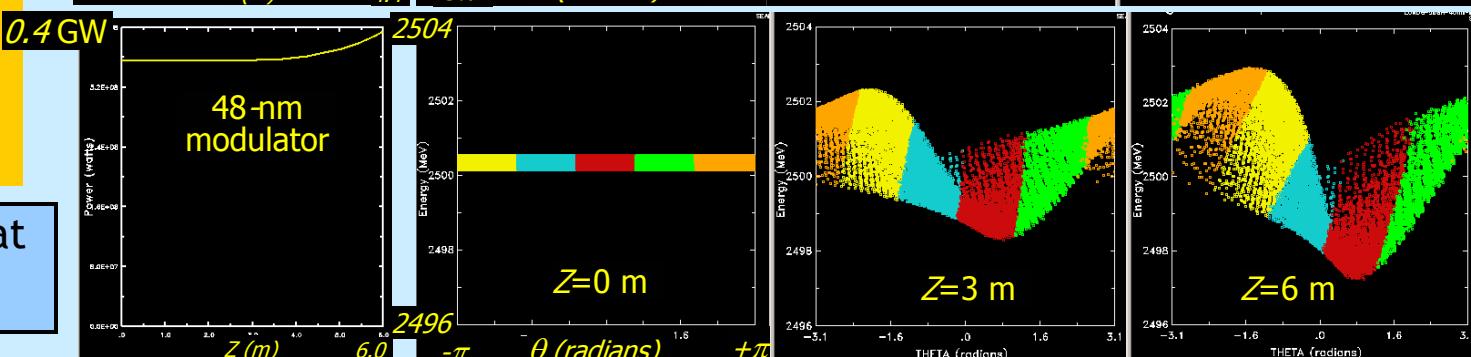
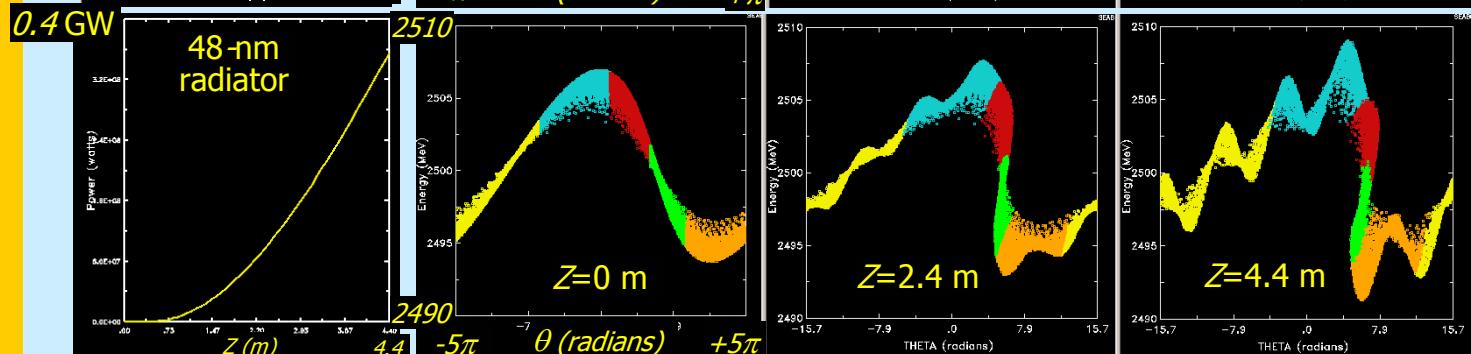
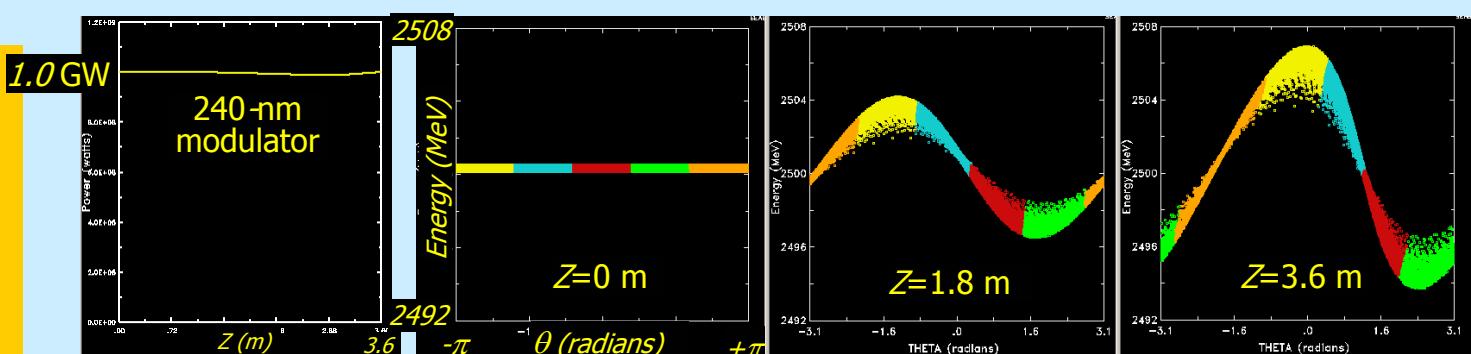


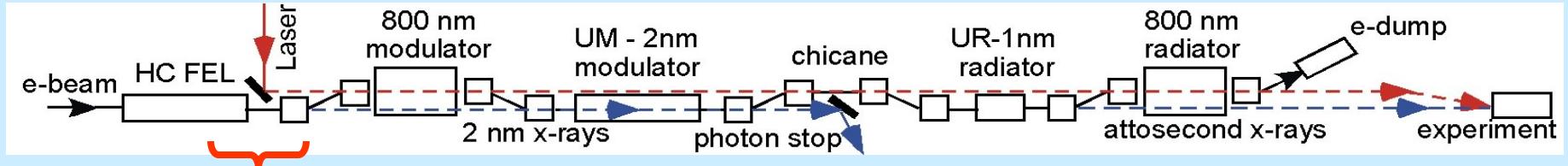
Power vs. Z γ - θ scatter plots

At each modulator,
radiation interacts
with “virgin” e-

At each harmonic
upshift $\lambda \Rightarrow \lambda/n$
(modulator to
radiator), macro-
particle phase
multiplied by n

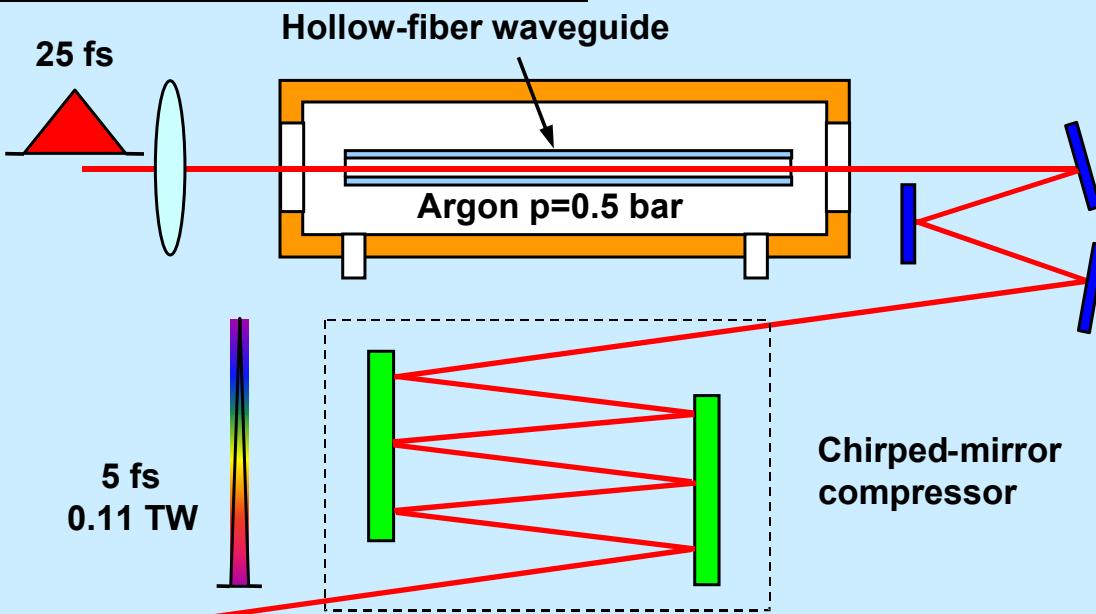
200 MW peak power at
2 nm wavelength





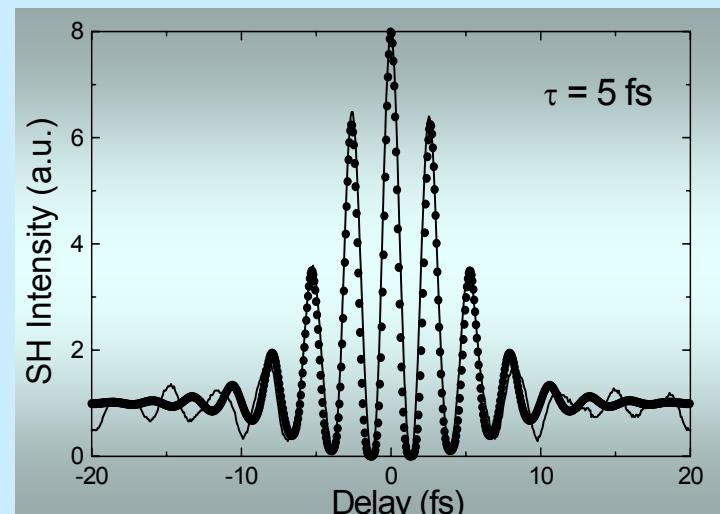
Sub-TW sub-10-fs laser pulses with carrier-envelope phase control

Courtesy Giuseppe Sansone



M. Nisoli *et al.*, Appl. Phys. Lett. **68**, 2793 (1996)
 M. Nisoli *et al.*, Opt. Lett. **22**, 522 (1997)

- ⇒ Guiding medium with a large diameter mode and a fast nonlinear medium with high damage threshold
- ⇒ Ultrabroad-band dispersion control by chirped-mirrors

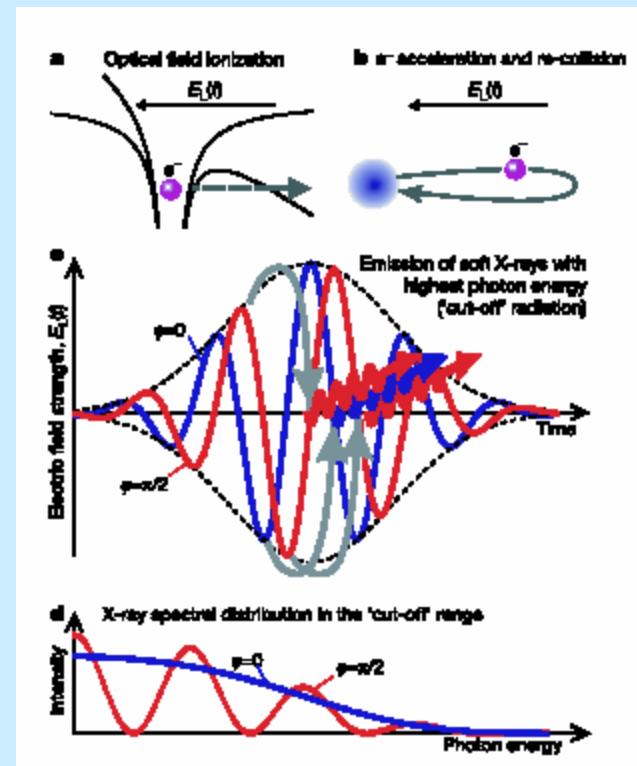
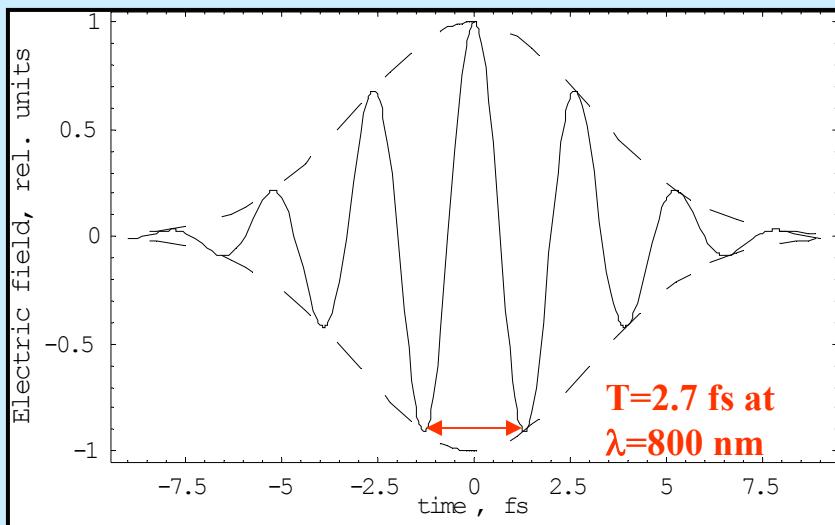


Few-cycle laser pulse

letters to nature

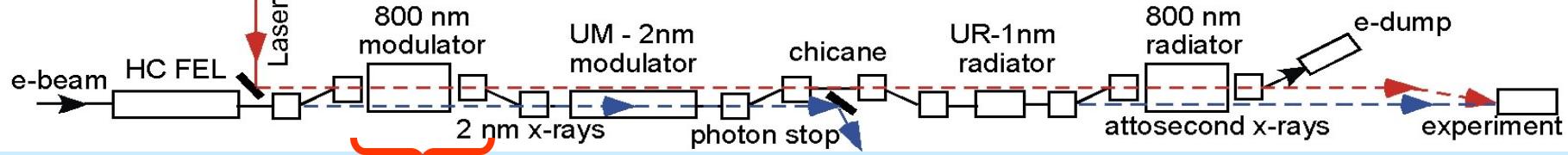
Attosecond control of electronic processes by intense light fields

A. Baltuska*, Th. Udem†, M. Uiberacker*, M. Hentschel*,
E. Goulielmakis*, Ch. Gohle†, R. Holzwarth†, V. S. Yakovlev*, A. Scrinzi*,
T. W. Hänsch† & F. Krausz*

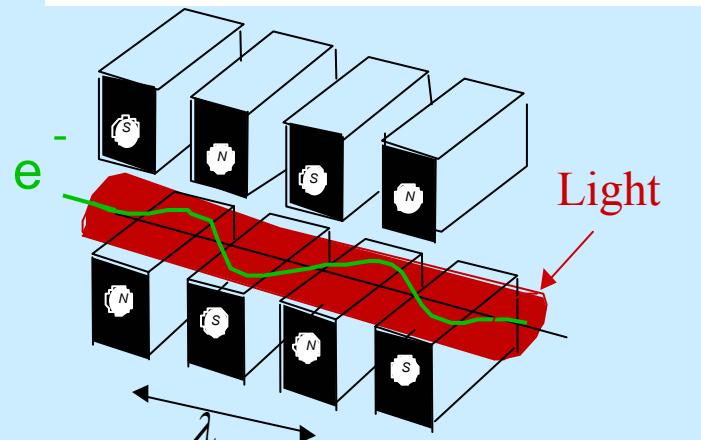


0.5 mJ, 5-fs optical pulses at 1 kHz S.
Sartania et.al., Optics Letters, 22, (1997)
1562

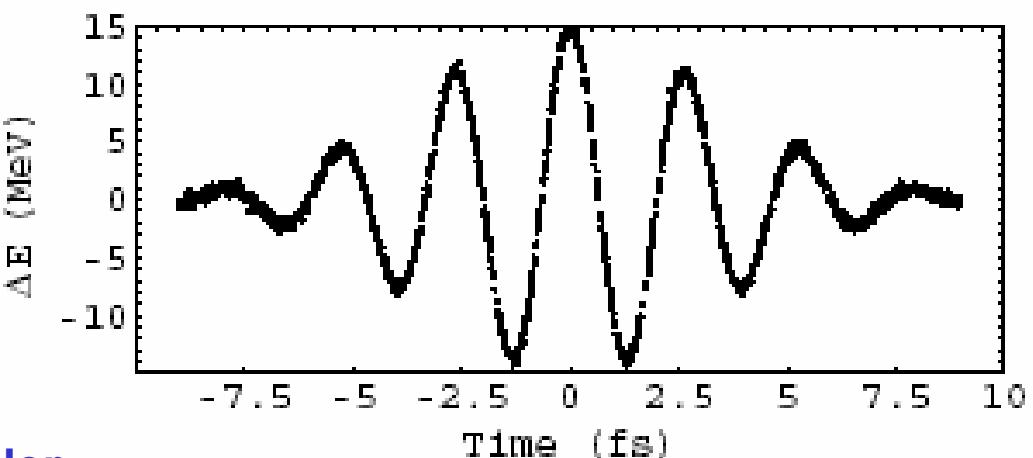
Carrier-envelope phase control allows to lock the maximum of the electric field to
the maximum of the envelope – D. Jones et.al., Science, 288, (2000)635



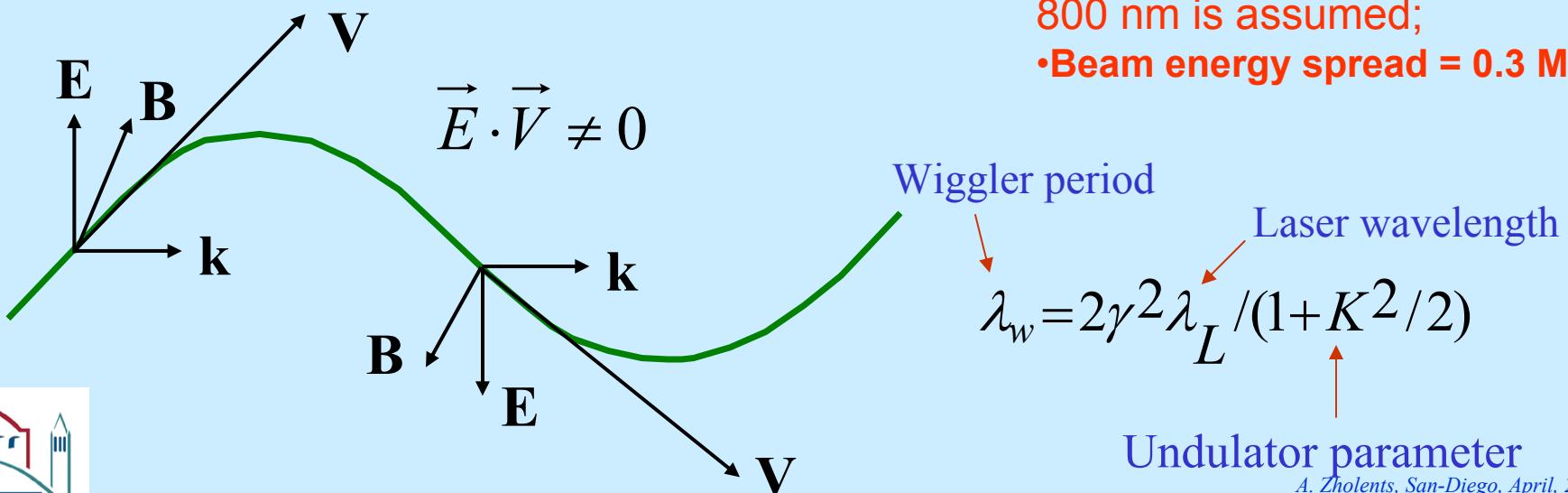
Energy modulation along the electron bunch



Electron trajectory through wiggler with two periods

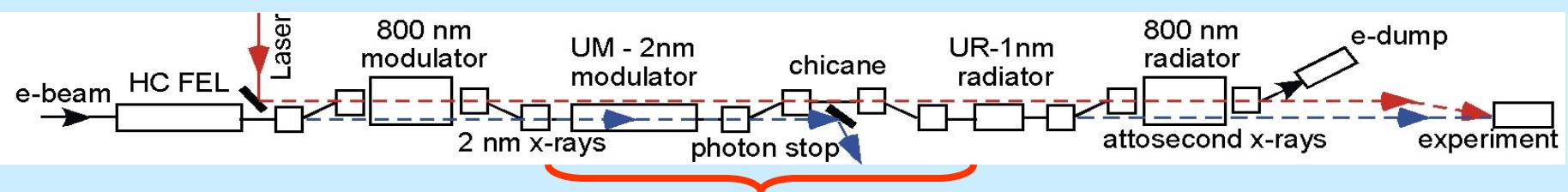


- 1 mJ, 5-fs optical pulses at 800 nm is assumed;
- Beam energy spread = 0.3 MeV

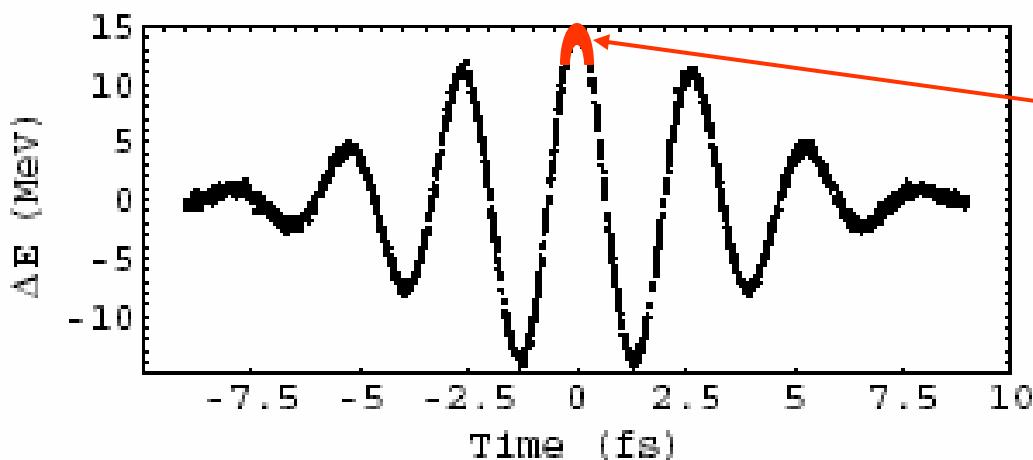
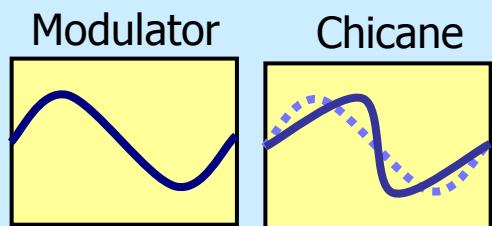


Undulator parameter

A. Zholents, San-Diego, April, 2004



Energy modulation at 2 nm and bunching at 1 nm



Modulator is set that only electrons at a top energy interact with x-ray pulse from Harmonic Cascade FEL

Define bunching by solving standard FEL equations

$$\frac{d\nu}{d\hat{z}} = -\Omega^2 \sin(\theta) \text{ and } \frac{d\theta}{d\hat{z}} = 2\pi\nu$$

$$\nu = 2N_u \frac{\Delta\gamma}{\gamma_R} \quad \Omega^2 \approx 2N_u \frac{\Delta\gamma_m}{\gamma_R}$$

$$b(\nu_0) \equiv \langle e^{in\theta} \rangle \propto J_n(n\pi\Omega^2\chi(\pi\nu_0)) e^{in\phi(\nu_0)} e^{-0.5(n(2\alpha+0.5)\sigma_\nu)^2}$$

Electron energy at the entrance of 2-nm modulator

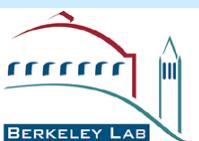
due to energy spread

$$\nu_0(t) \approx 2N_u \frac{\Delta\gamma_m}{\gamma_R} \left(\cos \frac{2\pi c}{\lambda_L} t - 1 \right) + \delta\nu \rightarrow \nu_0(t) \sim t^2$$

$$\chi(x) \equiv \sqrt{\left((2\alpha+1) \frac{\sin x}{x} \right)^2 + \frac{1}{x^2} \left(\frac{\sin x}{x} - \cos x \right)^2}$$

$$\phi(\nu_0) = \pi\nu_0(2\alpha+1) + \tan^{-1} \left(\frac{1}{\pi\nu_0} + \frac{1}{\tan \pi\nu_0} \right)$$

$$\alpha \equiv R_{56} / 2N_u \lambda_x$$



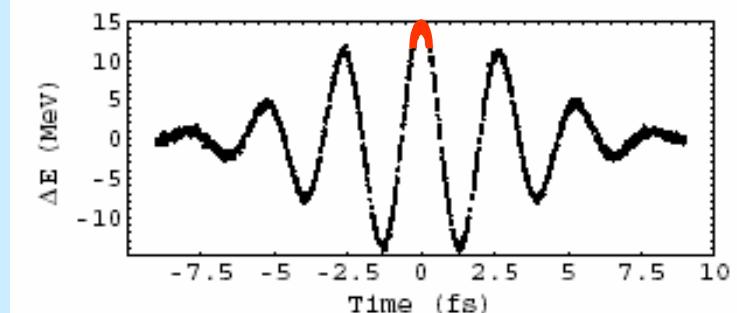
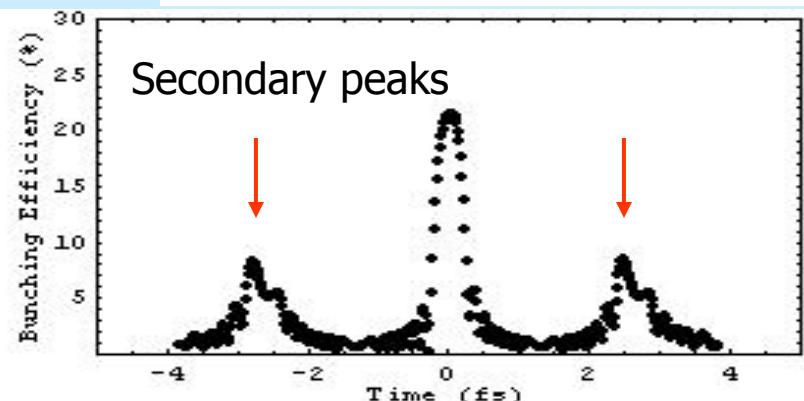
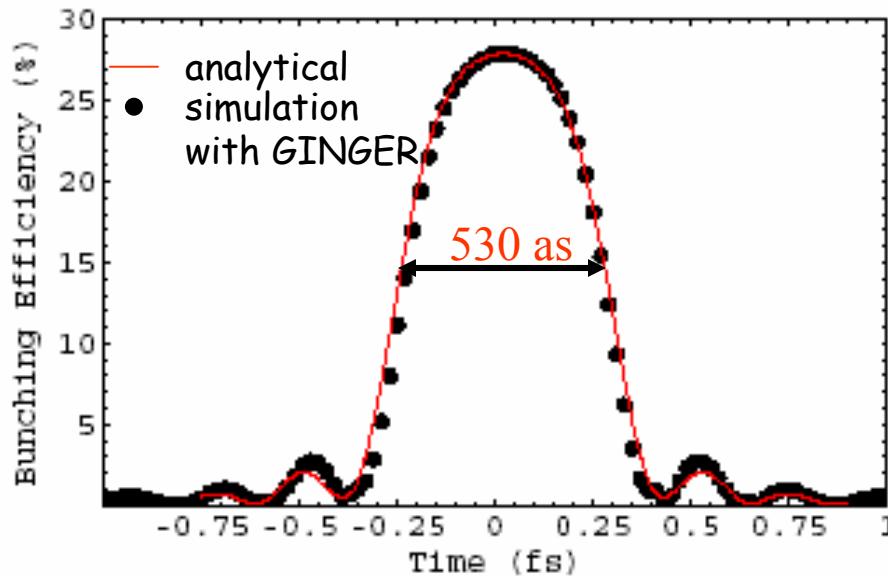
LUX electron beam parameters:

beam energy = 3 GeV

emittance = 2 mm-mrad

energy spread = 0.3 MeV

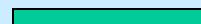
peak current = 500 A



Different timing parameters (shown not to scale)



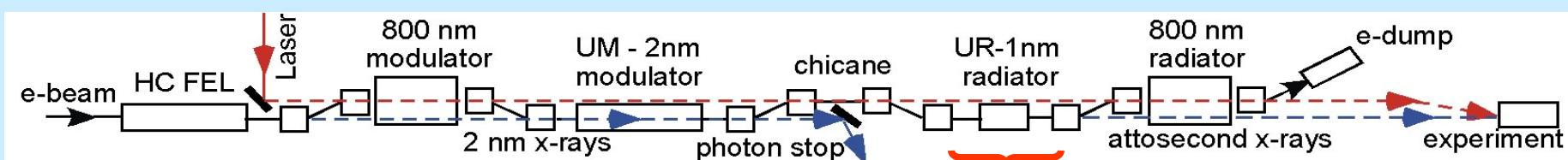
~100 fs - pulse length of 2 nm radiation



~10 fs – slippage length in 2 nm modulator



100 attosecond pulse

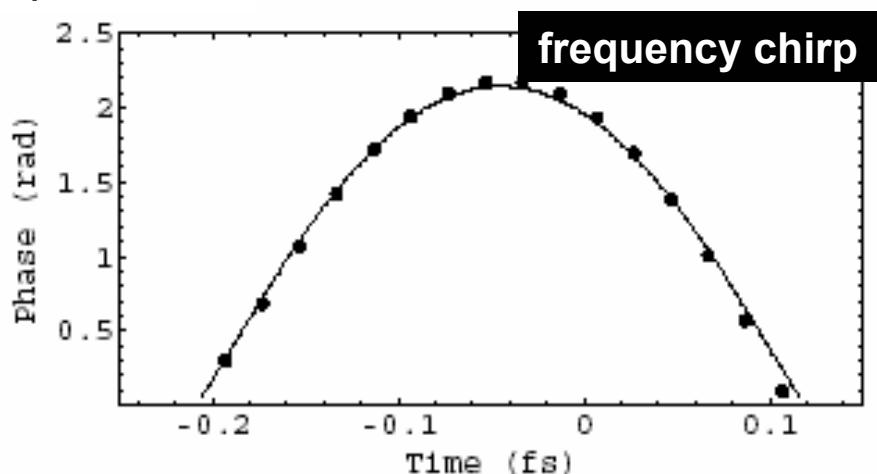
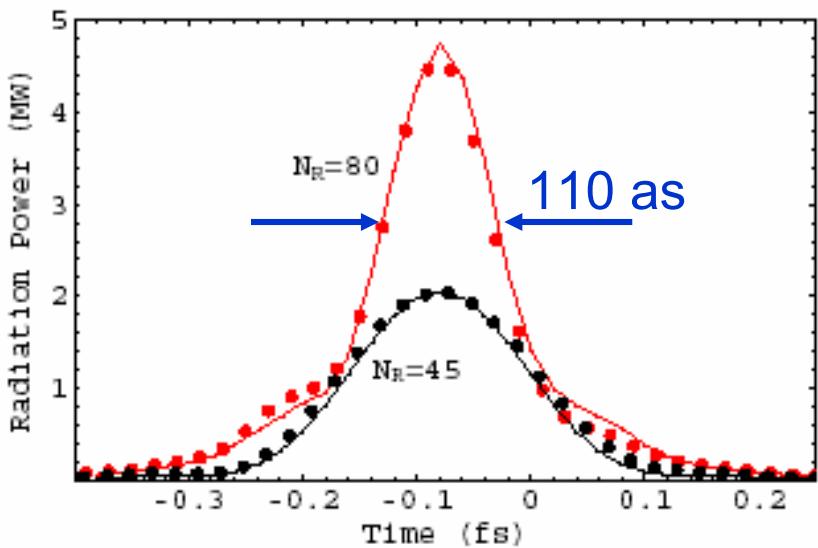


Bunched electrons radiate in the 1 nm undulator radiator

$$E(t) = \text{Re}\left\{\tilde{E}(t)e^{-i\omega_x t}\right\} \quad \tilde{E}(t) \propto \sum b_n(\nu_{0,j}) H\left(\frac{N_R}{2} - \left(j - \frac{N_R}{2} + \frac{ct}{\lambda_x}\right)\right)$$

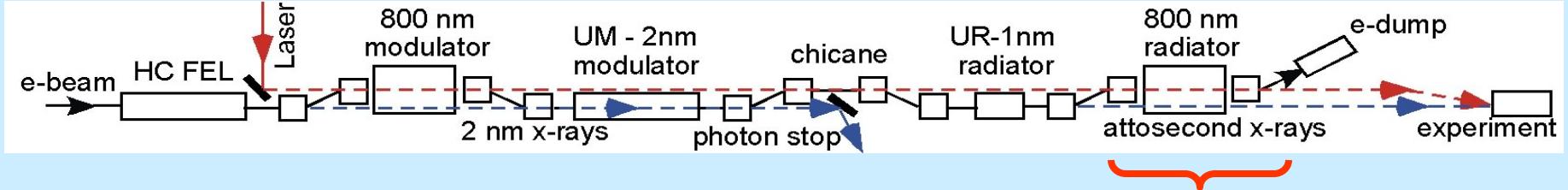
step function

$$I(t) \propto |\tilde{E}(t)|^2$$



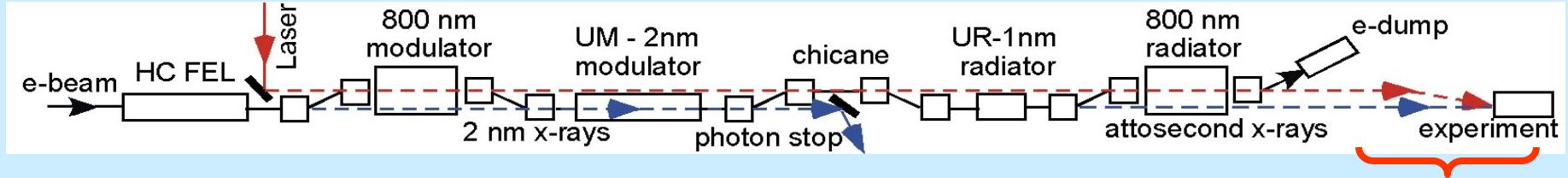
Pulse duration is shorter than width of the pulse on the “bunching” plot due to a destructive interference of the radiation from the “head” and the “tail”.

Phase modulation in the radiation field appears as a result of the time variation in the magnitude of the energy modulation of the “attosecond” electrons. Further compression to ~80 as FWHM might be possible!

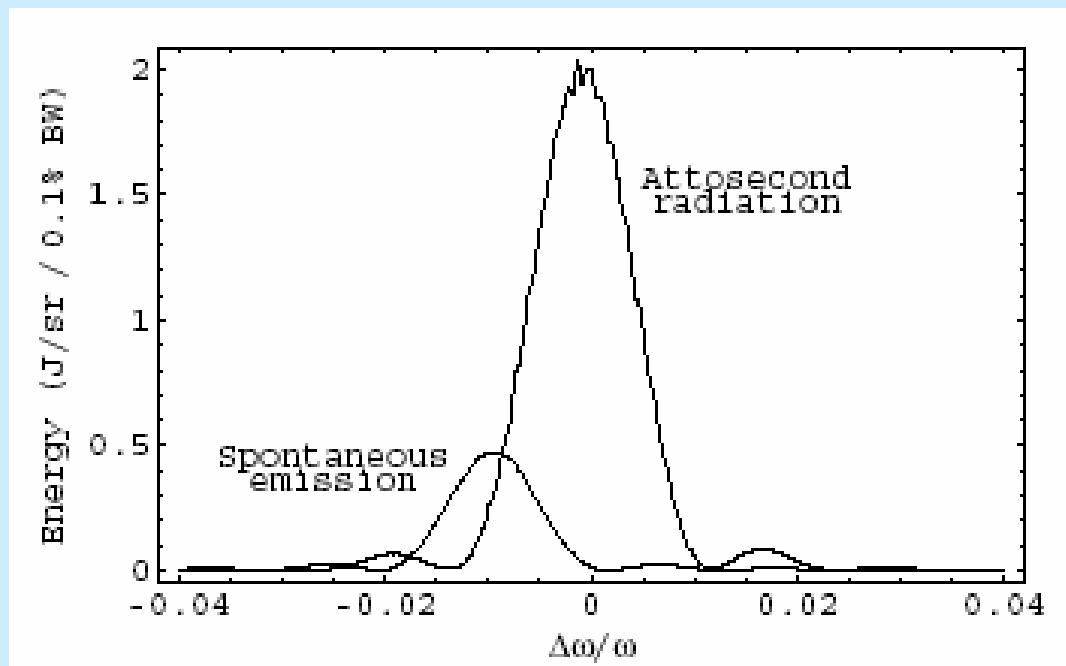


Synchronization

- In principle optical **pump** pulse and attosecond x-ray **probe** pulse are absolutely synchronized since both pulses are originated by the same source.
- 800 nm radiator produces few fs pulses that can be cross-correlated with the “seeding” laser pulse.



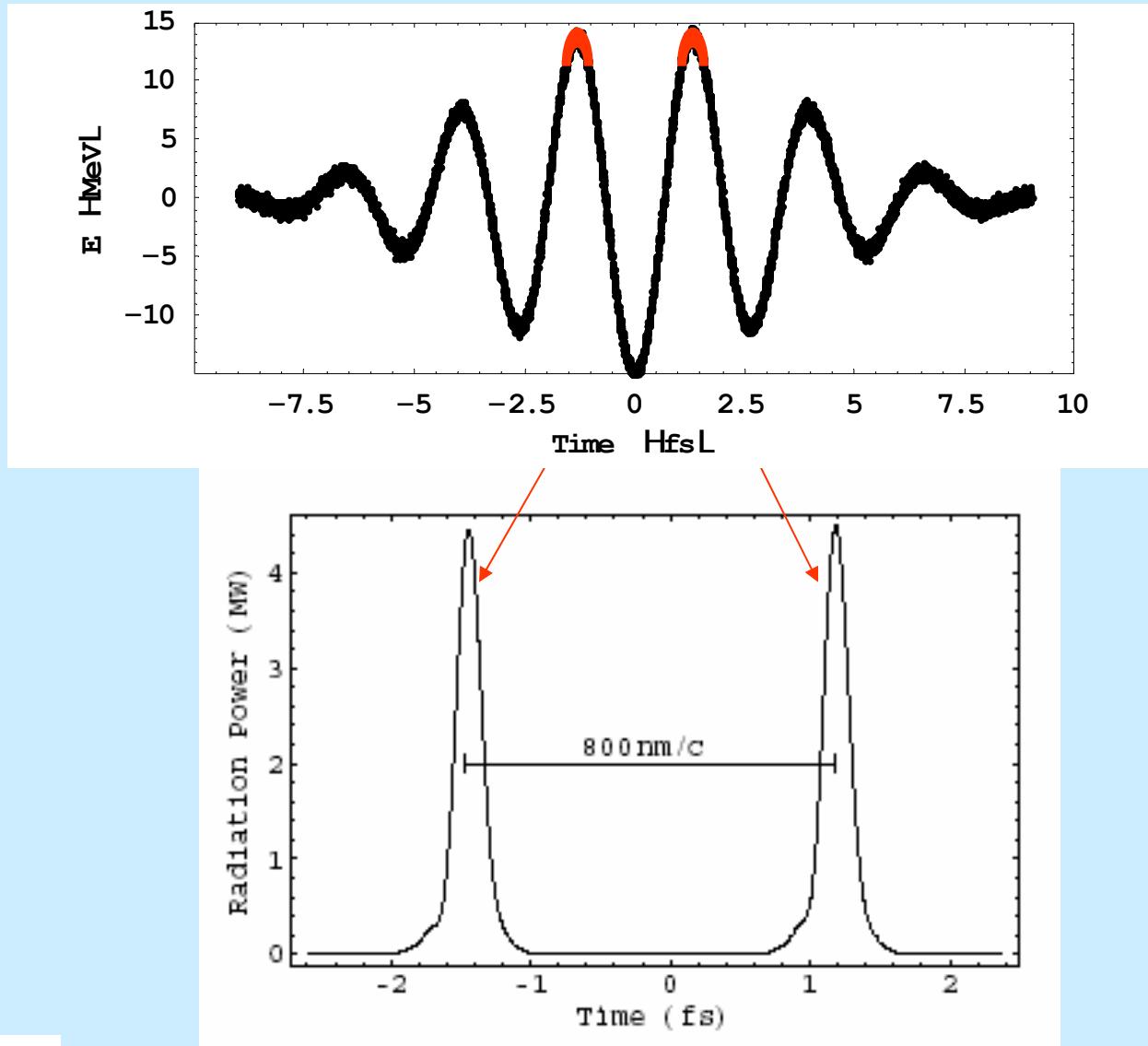
Radiation spectra



- Coherent radiation of the “attosecond” electrons dominates over the spontaneous emission from the entire bunch electrons (GINGER output).
- Spectral peak of the spontaneous emission is shifted into the red. A double grating monochromator with pathlength compensation can be used *).

*) P. Villoresi, Applied Optics, vol.38, p.6040 (1999).

Production of two attosecond pulses by shifting laser phase on 180 degree.



Other variations are also possible.

Summary

- 1) Production of the attosecond x-ray pulses uses:
 - transversely and temporally coherent x-ray light
 - intense few-cycle optical pulse with carrier-envelope phase control
- 2) ~ 100 attosecond x-ray pulses at 1 nm are feasible
 - attosecond pulses at other wavelength can be produced with the same technique
- 3) Shorter than 100 attosecond pulses might be possible.
- 4) There is an absolute synchronization between optical pump and x-ray probe pulses.
- 5) A proposed scheme for a production of attosecond x-ray pulses can be added to a Harmonic Cascade FEL at a relatively modest cost compared to what it will cost to build a primary facility.

